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(54) Apparatus for sensing short circuit faults

(57) In the supply system of a direct-on-line starting induction motor, fault conditions are distinguished from start-up by evaluating (i) the amplitude I of the line current and (ii) the phase angle Φ between line current and voltage and determining whether the coordinate position of these parameters in the I–Φ plane (Fig. 7) lies above or below a "reference" line 13′. The line 13′ reflects the motor starting characteristics, and since the latter vary with voltage the line 13′ is also varied (13′a, 13′b) as a function of line voltage V.

In a practical implementation (Fig. 3) faults are detected by determining whether

$$\Phi_v - \left(\frac{1}{m}\right) I < \Phi_{cv}$$

where Φ_v is proportional to both Φ and V, m is a constant and Φ_{cv} is a function of V. An evaluating arrangement is provided for each phase of the supply.

FIG. 3

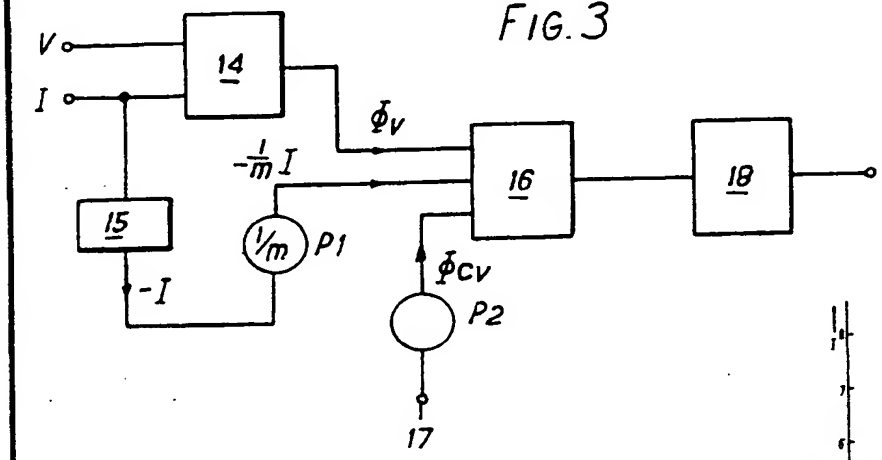
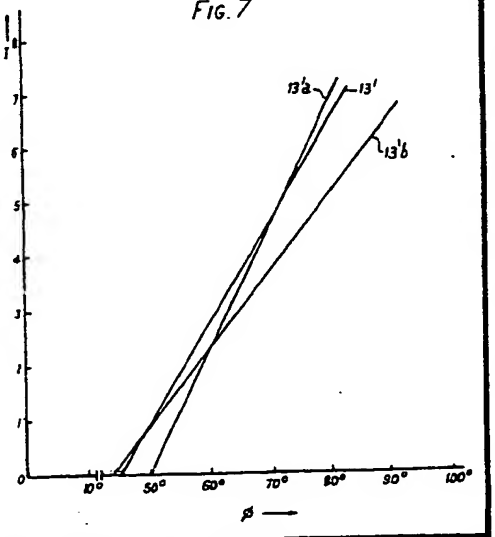


FIG. 7



Certain of the mathematical formulæ appearing in the printed specification were submitted in formal form after the date of filing. The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.

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FIG. 1

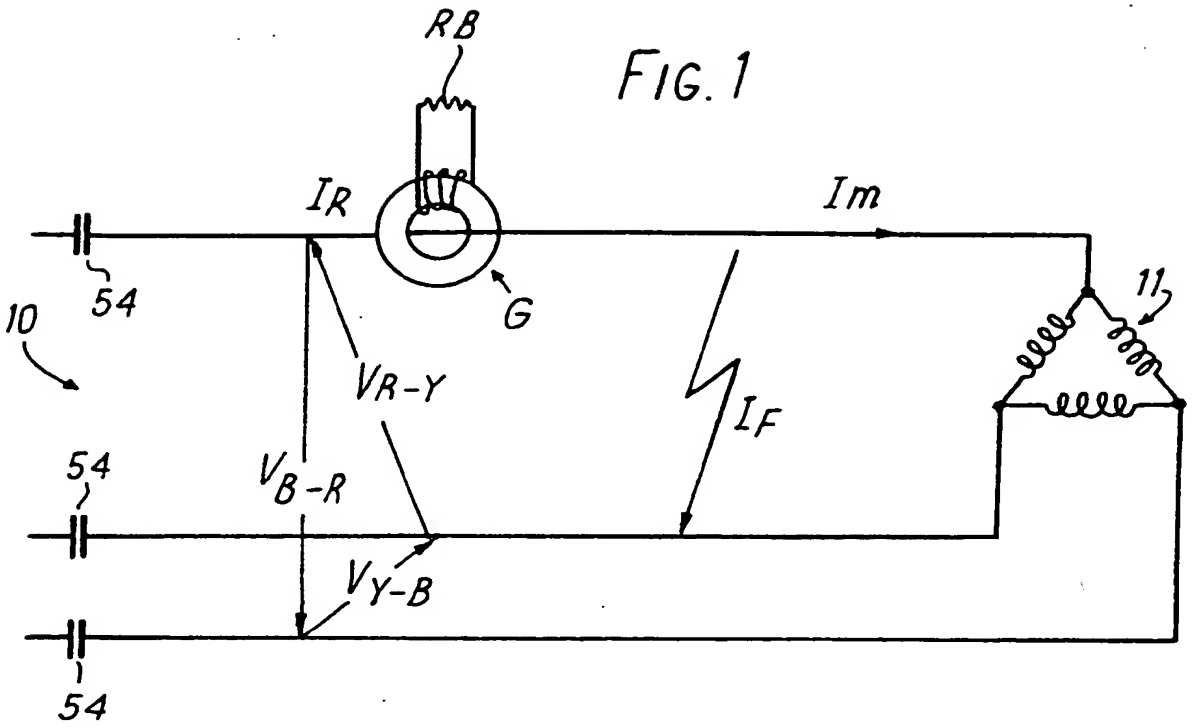

FIG. 3

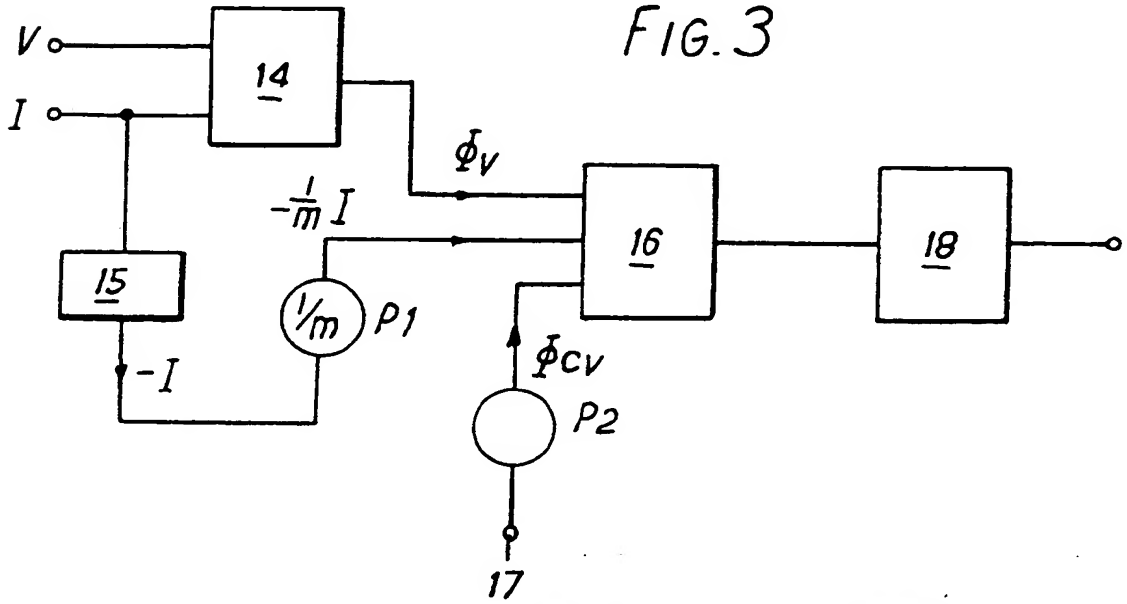

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FIG. 2

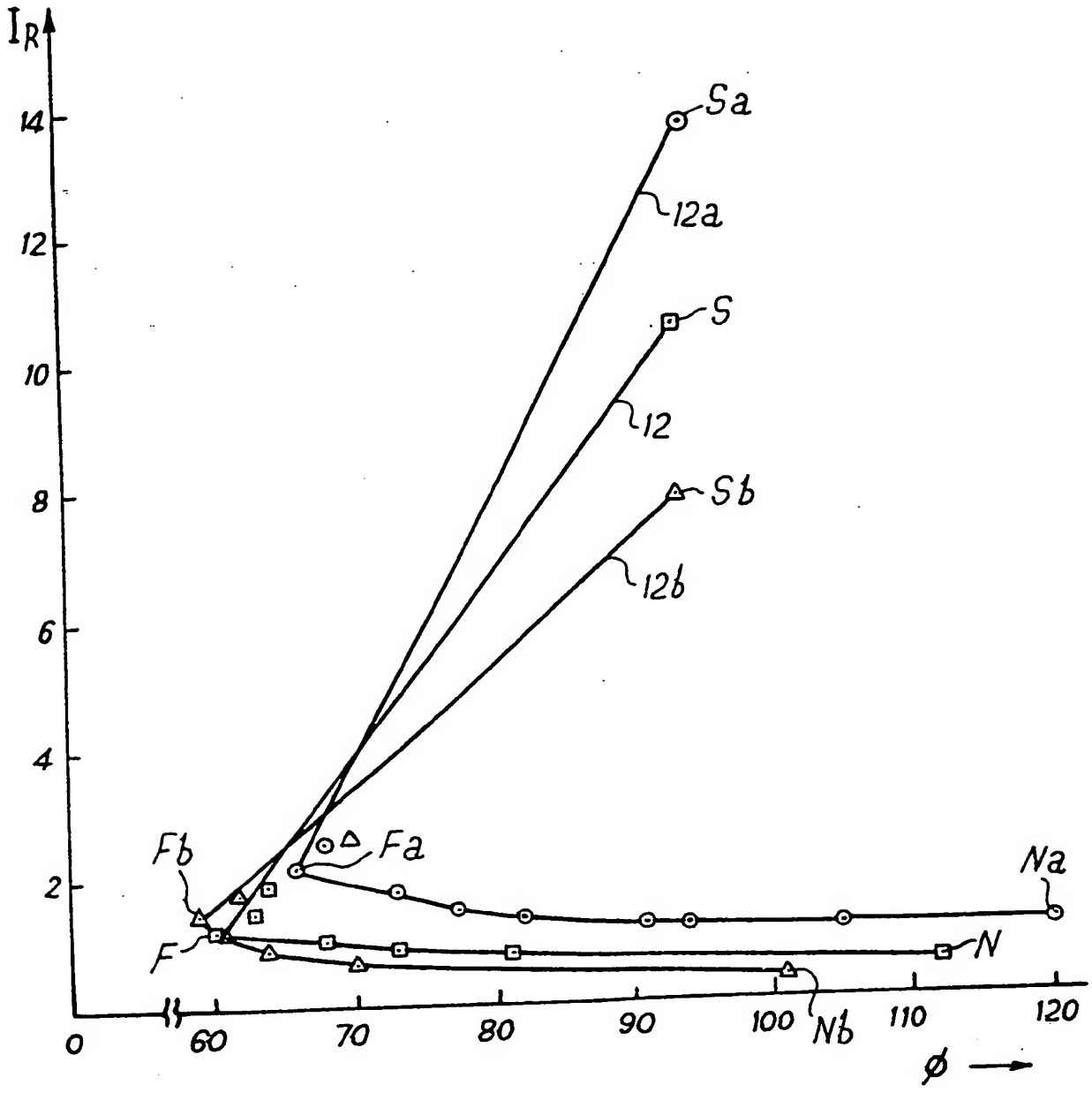

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FIG. 4

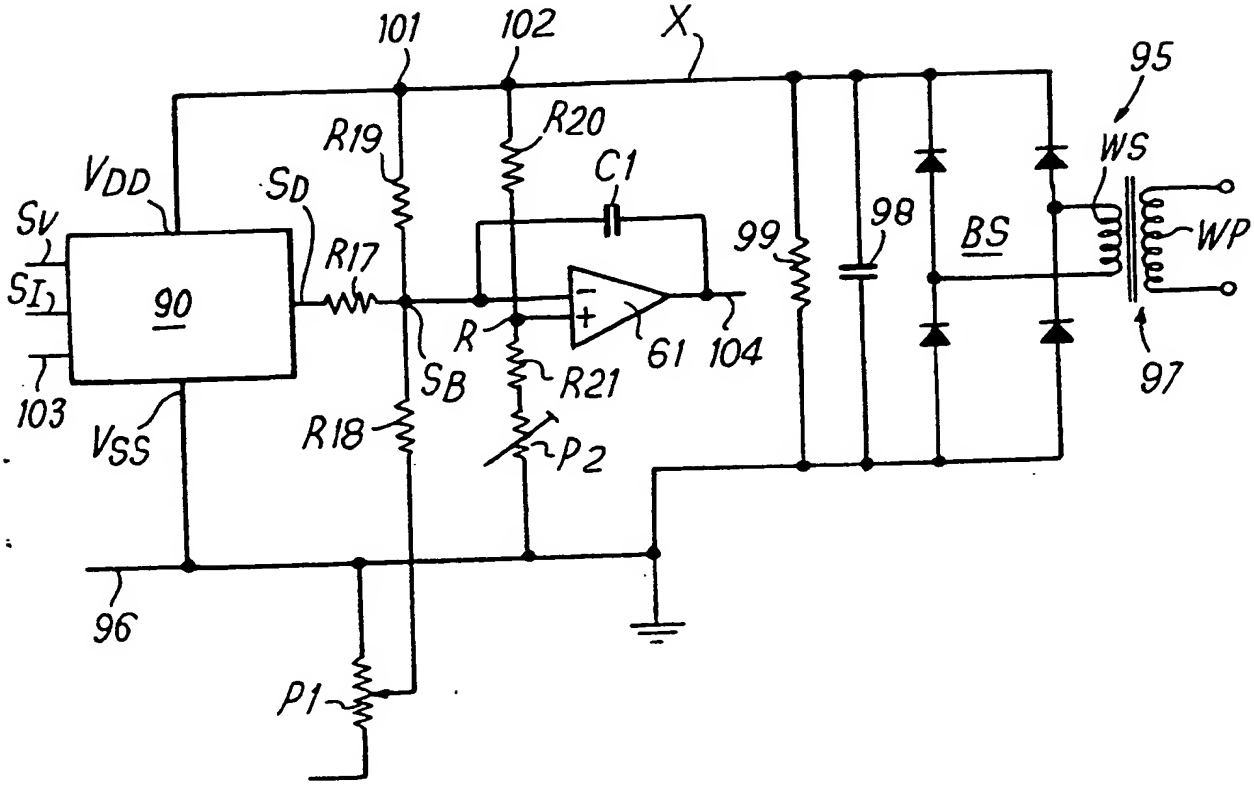

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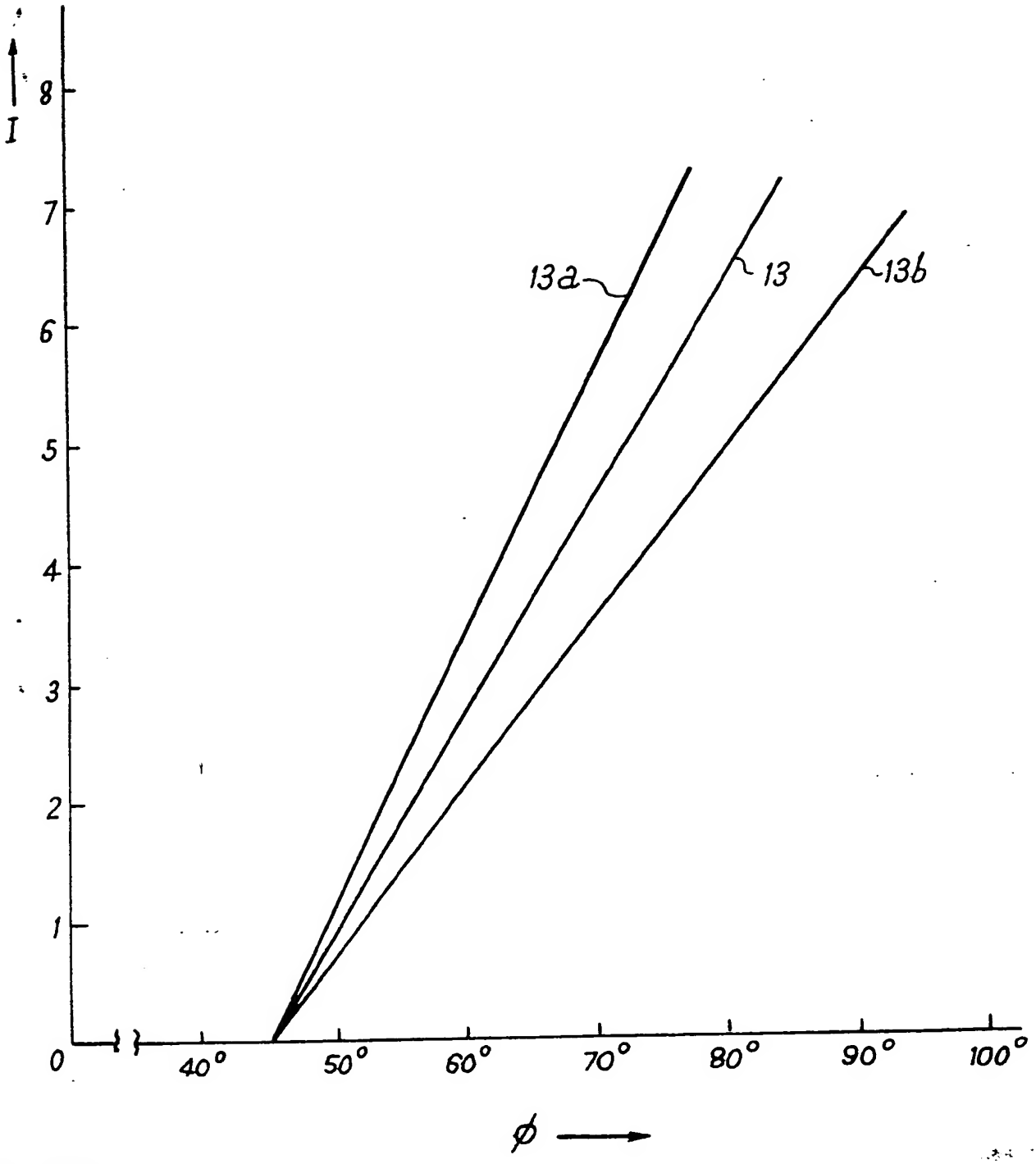
FIG. 5



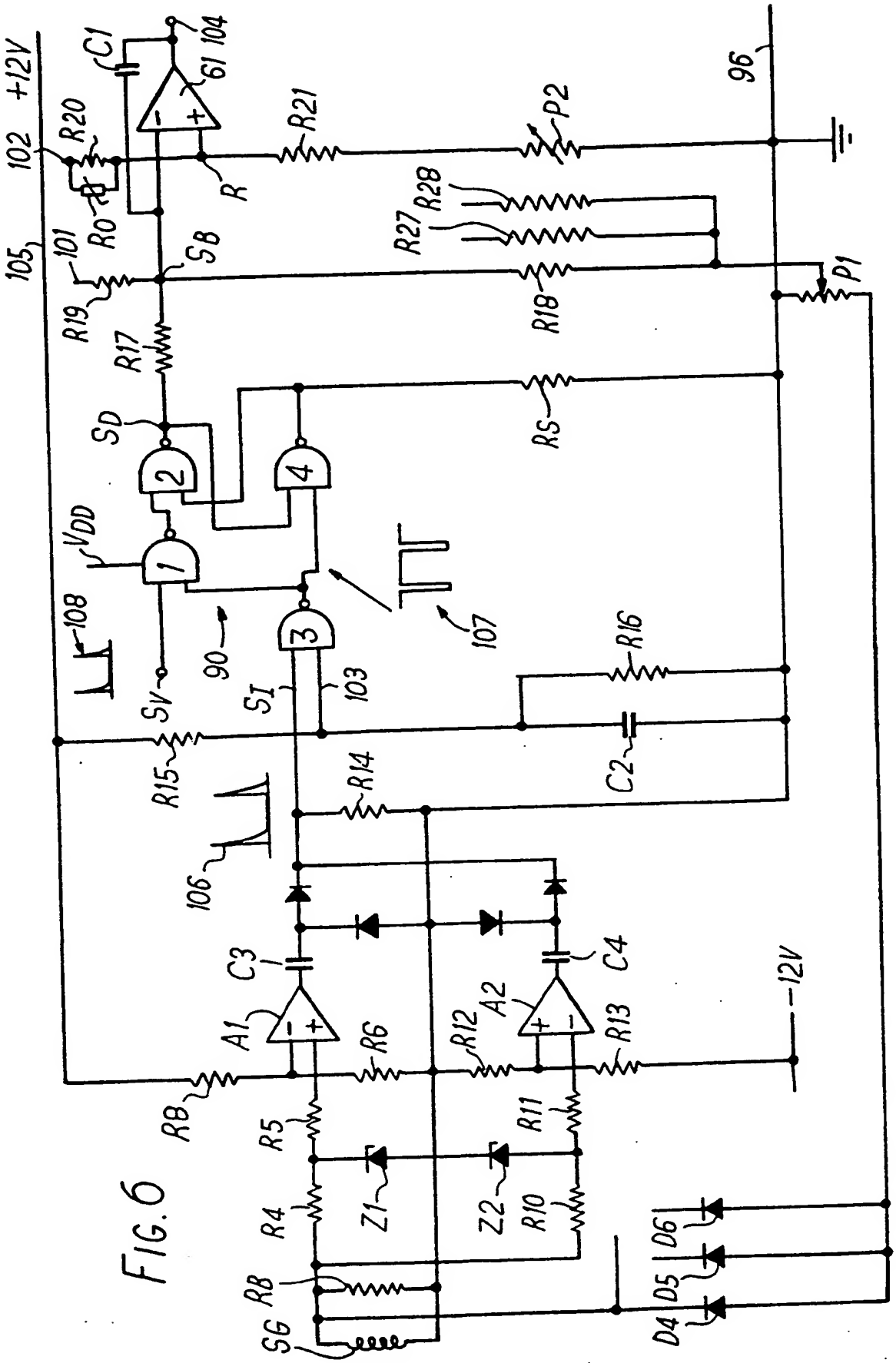


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FIG. 7

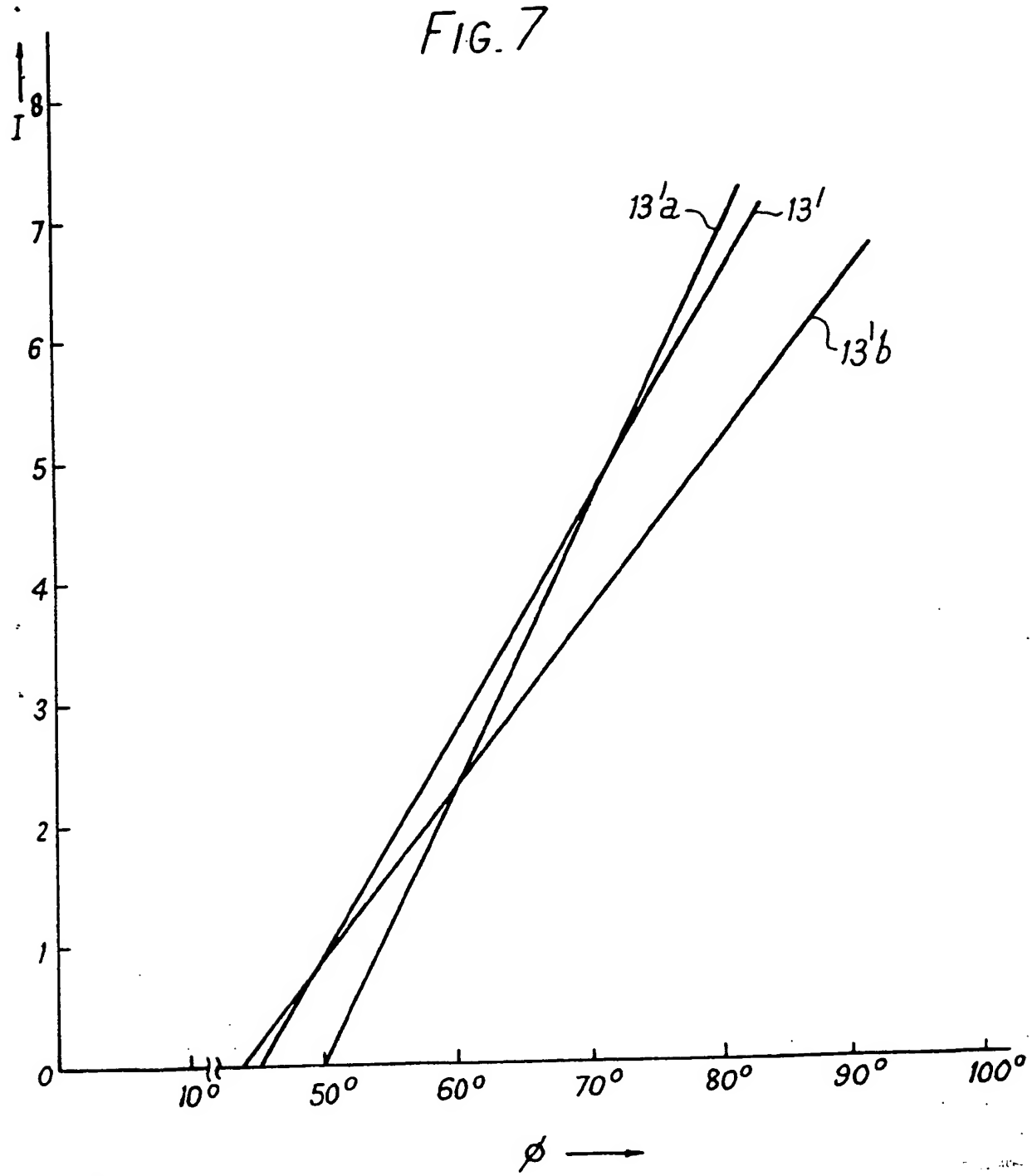

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FIG. 8

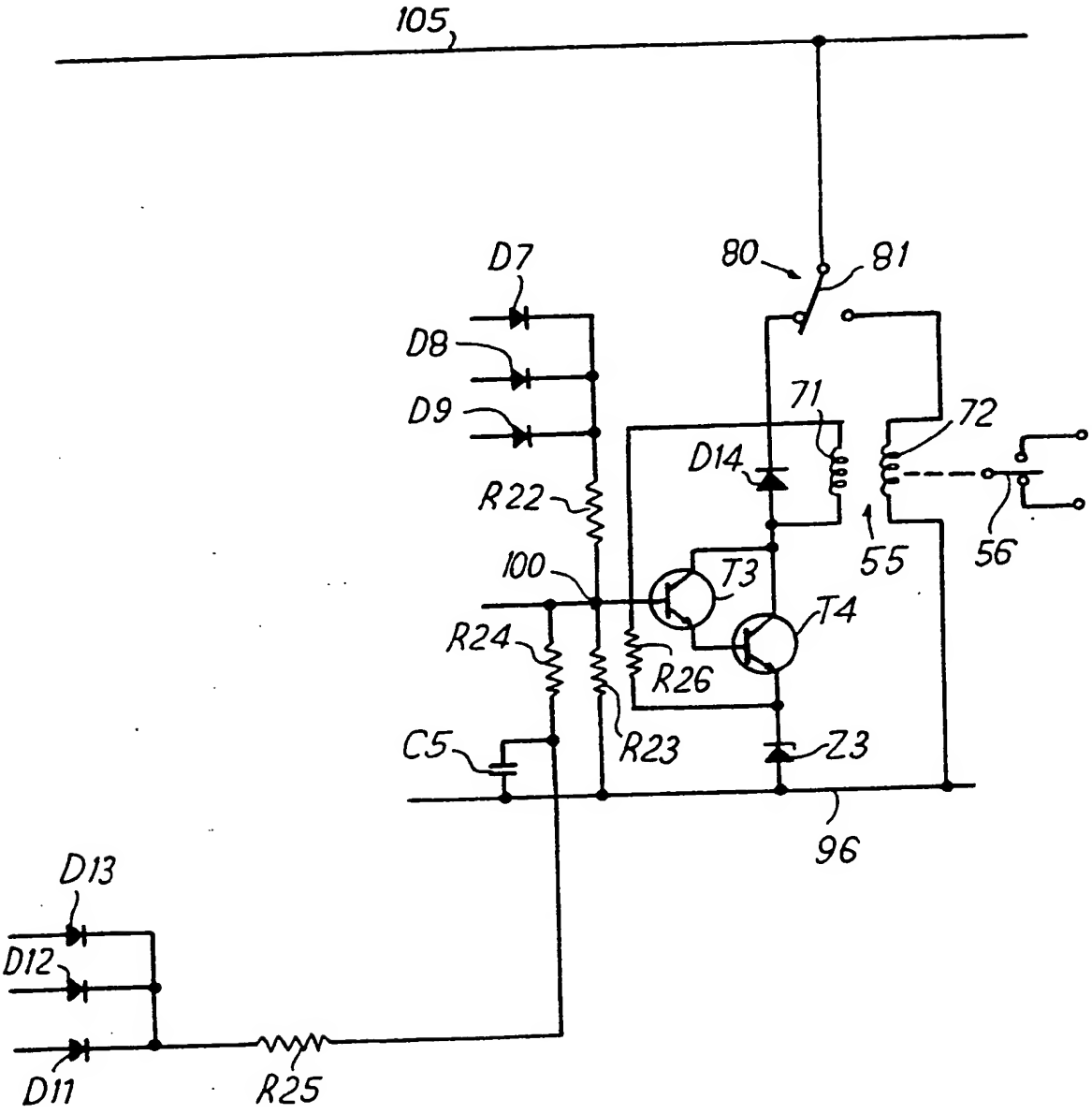

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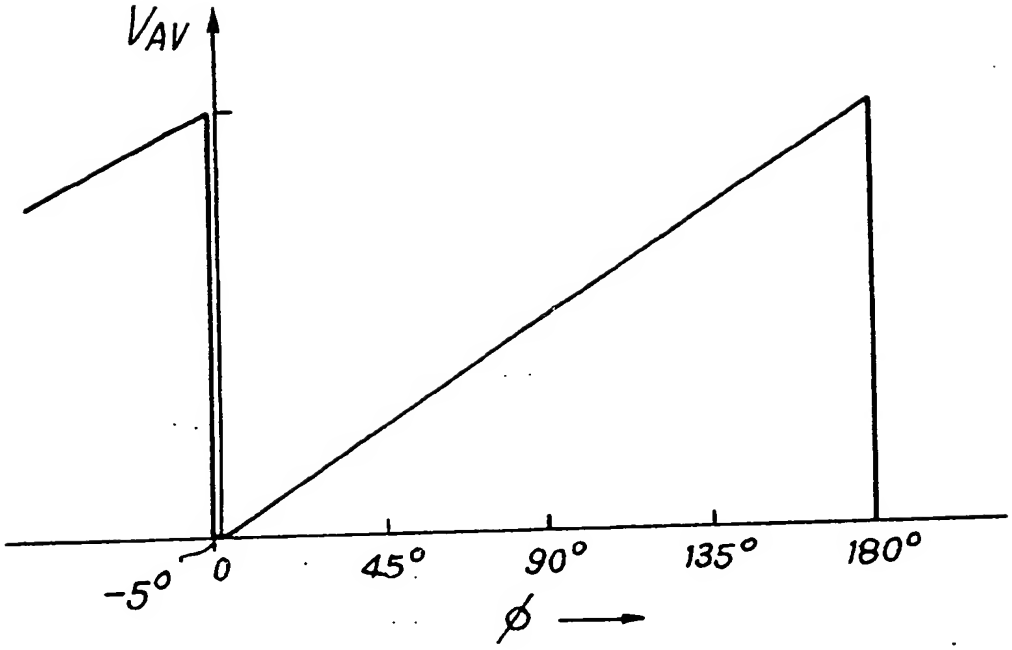
FIG. 9



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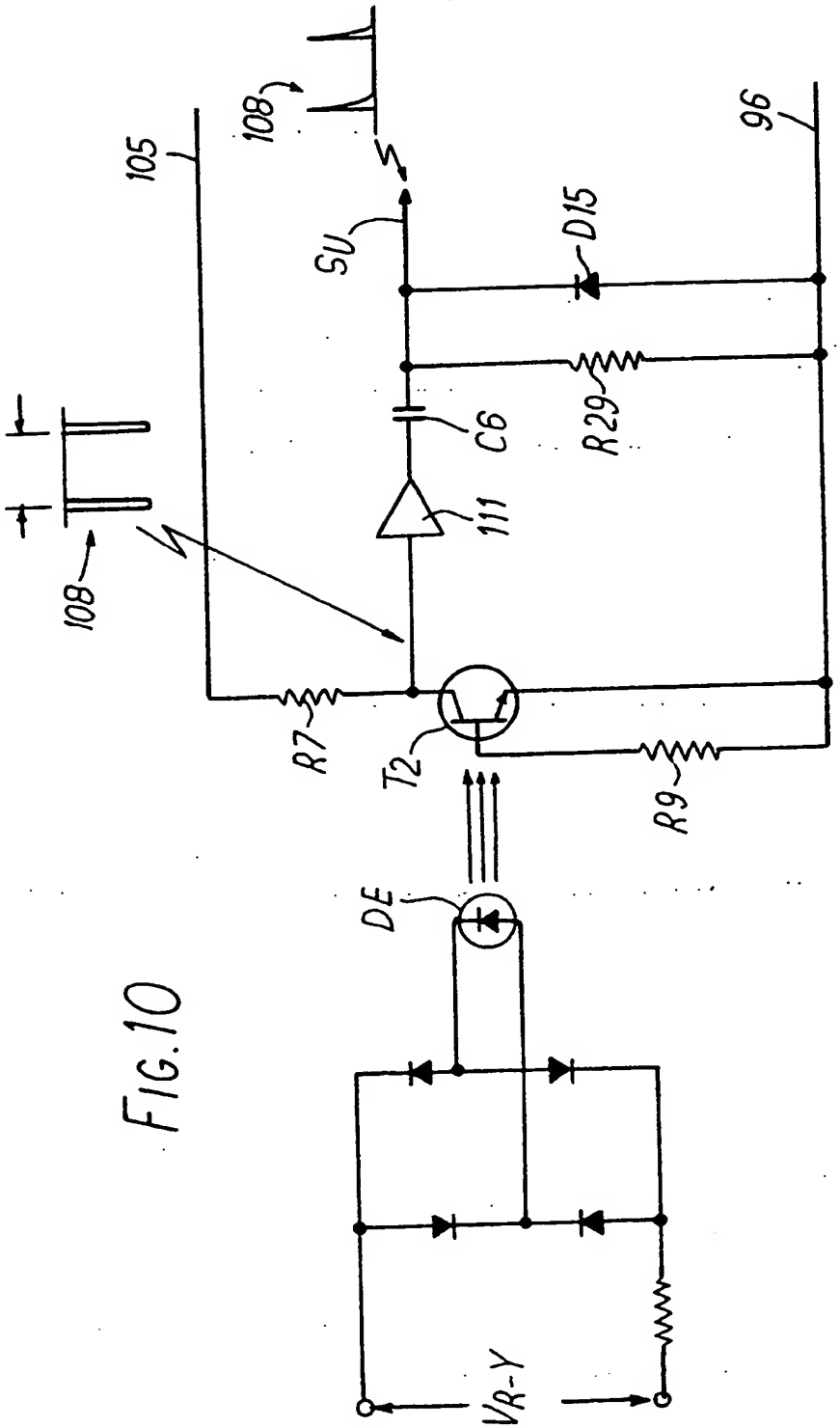

FIG. 10

SPECIFICATION

Apparatus for sensing short circuit faults

This invention relates to apparatus for sensing short circuit faults in alternating current supply lines and especially, although not exclusively, to the protection of alternating current supplies when arranged for supplying direct-on-line starting three phase squirrel cage induction motors.

The present invention has arisen from the consideration of a particular problem which is met in the use of direct-on-line starting three phase squirrel cage induction motors in coal mines but is of more general application.

The particular problem mentioned above is that of providing adequate protection of a three phase supply against short circuits between the phase lines or to a neutral point while permitting direct-on-line starting of three phase squirrel cage induction motors connected to the three phase supply. That this is a problem is due to the fact that the value of the starting current drawn in each line by such a motor during direct-on-line starting has several times, for example four to ten times, the amplitude of the current drawn when the motor is running under full load conditions and consequently no protection based merely upon sensing of the amplitude of the currents drawn is practicable for short circuit faults which are drawing currents which are of less amplitude than that of the motor starting current. While a conventional motor overload protection will respond to short circuit current in this range, its inherent time delay will be long enough to permit damage to be done to the supply and possibly also the motor.

Direct-on-line starting is used for three phase squirrel cage induction motors in coal mines and other hazardous environments because simplicity in operating equipment is found to be essential there. However, the risk that supply lines may be damaged or cut is always present and it is also essential that the consequent risk of fire or explosion started by electrical fault arcing should be minimised and eliminated if at all possible. Hence there is a requirement for means which will isolate the source of three phase supply from any short circuit fault on the supply lines.

According to one aspect of the present invention there is provided apparatus for sensing short circuit faults in alternating current supply lines, the apparatus including means for sensing line current in an alternating current supply line and producing signals representative of the sensed amplitude and a phase of line current flowing in operation, means for sensing the line to line or line to neutral voltage of the supply line and producing a signal representative of a phase of the line to line or line to neutral voltage, difference means coupled to receive the signals which are representative of the phases of the said current and voltage and arranged to produce in response thereto a signal having a measure which varies substantially directly with difference between the said phases, and means for comparing a relationship of the signal representative of sensed current amplitude and the said signal produced by the difference means with a predetermined relationship of amplitude and phase difference and producing in response thereto an output signal representative of whether or not the sensed current amplitude is larger than the corresponding amplitude as determined by the said predetermined relationship for the said difference between the said phases, the said predetermined relationship being such as to vary with the said line to line or line to neutral voltage. The apparatus may include means for interrupting at least the said supply line in response to the said output signal being representative of the sensed current amplitude being larger than the said corresponding amplitude, the interrupting means being coupled to the comparing means to receive the said output signal.

To protect a three phase supply an embodiment of the present invention has means for sensing each line current in three phase lines and producing signals representative of the sensed amplitudes and phases of the line currents flowing in operation, means for sensing the line to line or line to neutral voltages of the supply lines and producing signals representative of phases of the line to line or line to neutral voltages, difference means coupled to receive the signals which are representative of the said phases and arranged to produce in response thereto three signals each of which has a measure which varies substantially directly with difference in phase between the respective line current and line to line or line to neutral voltage of a respective one of the three phase lines, means for comparing for each phase line a relationship of the respective one of the signals representative of sensed current amplitude and the respective one of the signals produced by the difference means with a predetermined relationship of amplitude and phase difference and producing in response thereto an output signal representative of whether or not any one or more of the sensed current amplitudes is larger than the corresponding amplitude as determined by the respective predetermined relationship for the respective one of the said differences in phase between the respective line current and line to line or line to neutral voltage, and means for interrupting the three supply lines in response to the said output signal being representative of any one or more of the sensing current amplitudes being larger than the said corresponding amplitude, the interrupting means being coupled to the comparing means to receive the said output signal, and the respective predetermined relationships

being such as to vary with the respective line to line or line to neutral voltages.

According to another aspect of the present invention there is provided apparatus for sensing short circuit faults in alternating current supply lines, the apparatus including means for sensing line current in an alternating current supply line and producing a signal representative of the sensed amplitude and current phase triggering pulses each corresponding to a selected phase of line current flowing in operation, means for sensing the line to line or line to neutral voltage of the supply line and producing voltage phase triggering pulses each corresponding to a selected phase of the line to line or line to neutral voltage, bistable means coupled to receive the said current and voltage phase triggering pulses and arranged to produce in response thereto a train of phase difference pulses each having a leading edge initiated by a respective voltage phase triggering pulse and a trailing edge initiated by a respective current phase triggering pulse whereby the width of the pulse varies substantially directly with difference between the said phases, means for comparing a relationship of the signal representative of sensed current amplitude and an average value established by the train of pulses produced by the difference means with a predetermined relationship of amplitude and phase difference substantially of the form $y = a(x - b)$ where y = amplitude, x = phase difference and a and b are independent of x and y and producing in response thereto an output signal representative of whether or not the sensed current amplitude is larger than the corresponding amplitude as determined by the said predetermined relationship for the said diference between the said phases, and means for interrupting at least the said supply line in response to the said output signal being representative of the sensed current amplitude being larger than the said corresponding amplitude, the interrupting means being coupled to the comparing means to receive the said output signal. Since each leading edge of a pulse produced by the bistable means requires a voltage phase triggering pulse to initiate it, failure of the means for sensing line to line or line to neutral voltage results in absence of the phase difference pulses.

To protect a three phase supply an embodiment of the present invention has means for sensing each line current in three phase lines and producing signals representative of the sensed amplitudes and respective current phase triggering pulses each corresponding to selected phases of the line currents flowing in operation, means for sensing the line to line or line to neutral voltages of the supply lines and producing respective voltage phase triggering pulses respectively corresponding to selected phases of the line to line or line to neutral voltages, three bistable means coupled to receive respectively the triggering pulses which correspond to the respective lines and arranged to produce in response thereto three trains of phase difference pulses in each of which each pulse has a leading edge initiated by a respective voltage phase triggering pulse and a trailing edge initiated by a respective current phase triggering pulse whereby the width of the pulse varies substantially directly with difference in phase between the respective line current and line to line or line to neutral voltage of a respective one of the three phase lines, means for comparing for each phase line a relationship of the respective one of the signals representative of sensed current amplitude and an average value of the respective one of the trains of phase difference pulses with a predetermined relationship of amplitude and phase difference substantially of the form $y = a(x - b)$ where y = amplitude, x = phase difference and a and b are independent of x and y and producing in response thereto an output signal representative of whether or not any one or more of the sensed current amplitudes is larger than the corresponding amplitude as determined by the respective predetermined relationship for the respective one of the said differences in phase between the respective line current and line to line or line to neutral voltage, and means for interrupting the three supply lines in response to the said output signal being representative of any one or more of the sensed current amplitudes being larger than the said corresponding amplitude, the interrupting means being coupled to the comparing means to receive the said output signals.

Preferably the selected phases are 0° and 180° in each cycle of the voltage or current concerned.

In one three phase embodiment which is intended to be used to protect a three phase supply to a direct-on-line starting three phase squirrel cage induction motor, the predetermined relationship is, for each phase line, of the form

$$I_L = \frac{n}{R_B} . mk (\Phi - \Phi_c)$$

where I_L is the amplitude of the respective line current in amperes,

m is a dimensionless constant,

K is a factor which varies with line to line voltage for the phase and has units of voltage per degree,

R_B is a burden resistance in ohms,

n is the dimensionless ratio of a current transformer ie. the ratio of secondary to primary turns,

Φ is the phase difference between the respective line to line voltage and line current measured in degrees, and

Φ_c is a phase difference which varies with

line to line voltage for the phase and is measured in degrees.

When installed, apparatus which includes the interrupting means has the said interrupting means arranged to act on the supply line or lines at a position between the source of the supply and the said sensing means, ie. upstream of the sensing means.

This invention will now be described in more detail, solely by way of example, with reference to the accompanying drawings in which:

Figure 1 is a circuit diagram of supply connections to a three phase stator of an induction motor,

Figure 2 is a graphical representation of current amplitudes as functions of phase difference,

Figure 3 is a block diagram of an embodiment of the invention,

Figure 4 is a more detailed diagram of part of the embodiment of Fig. 3,

Figure 5 is a graphical representation of a set of voltage phase difference characteristics,

Figure 6 is a detailed circuit diagram of part of the embodiment of Fig. 3,

Figure 7 is a graphical representation of a further set of voltage-phase difference characteristics,

Figure 8 is a circuit diagram of another part of the embodiment of Fig. 3,

Figure 9 is a graphical representation of another voltage-phase difference characteristic, and

Figure 10 is a circuit diagram of a further part of the embodiment of Fig. 3.

In the description which follows, all references to three phase induction motors are references to three phase squirrel cage induction motors.

Fig. 1 shows schematically connections between a three phase electrical supply 10 and the stator windings 11 of a three phase induction motor connected for direct-on-line starting. The three phase connections include respective sets of circuit breaker contacts 54 which are closed when the motor is running.

In normal operation, three equal line to line voltages of amplitudes V_{R-Y}, V_{Y-B}, and V_{B-R} are established between pairs of three phase lines, known as the red, yellow and blue phases. This is illustrated in Fig. 1 where V_{R-Y}, V_{Y-B} and V_{B-R} are represented as existing between the three phase lines.

Corresponding to the three voltages there are three line currents of amplitudes I_R, I_Y and I_B which flow in the respective phase lines. These three currents are, under normal conditions, of equal amplitude. However, if a fault appears in which the insulation between two of the phase lines is more or less ineffective, a fault current, e.g. I_F, as illustrated in Fig. 1, flows between these two phase lines, and the respective line currents of the two lines increase to supply the fault current in addition to the stator currents. The presence of the fault alters the impedance between the two lines involved in the fault so that the phase angle between the respective line current and the respective line to line voltage of each of these two lines is reduced from that prevailing under normal conditions i.e. in the absence of the fault. Thus the presence of a fault increases the amplitudes of the line currents involved and reduces the phase angle between these line currents and the respective line to line voltages.

The phase angle relationship between a line current and the corresponding line to line voltage can be obtained by first producing two signals, one representative of the line current and the other representative of the corresponding line to line voltage, and supplying the two signals thus produced to a phase discriminator. Means for producing a voltage signal representative of the red line current is shown in Fig. 1 and comprises a current transformer G arranged to sense the red line current and a burden resistor R_B connected across the secondary winding of the transformer G. The voltage signal appears across the resistor R_B and is in phase with and proportional to the red line current. Another voltage signal which is in phase with the corresponding red to yellow line voltage V_{R-Y} can be provided by an electro-optical isolator arrangement.

In Fig. 2, which is a graph of the amplitude I_R of the red line current against phase difference between the red line current and the red to yellow line voltage V_{R-Y}, with the current lagging the voltage taken as a positive phase difference, the red line current amplitude characteristic of a three phase induction motor working with 100% of the supply voltage is represented by a curve 12 on which three points are marked, namely, S, F and N. The point S corresponds to the conditions of red line current amplitude and red phase difference at stall or starting of the motor. As the rotor (not shown) of the motor accelerates, the operating conditions move down the curve 12 from the point S to a point F corresponding to operation under full mechanical loading, the motor then working at maximum efficiency. If the motor is in fact not fully loaded, the operating conditions do not rest at the point F but move along the curve 12 from the point F towards the point N which corresponds to operation under zero mechanical loading. The actual point on the curve 12 at which the motor operates depends upon the mechanical loading and will lie at F or N or between these two points provided the motor is not overloaded. If the mechanical loading is constant, as in the case of a fan, the point remains stationary. If the mechanical loading varies between limits, as in the case of a coal cutter, the point will oscillate on the curve 12.

The portion of the curve from the point S to

the point F is found to be substantially straight and inclined at an acute angle to the positive value part of the phase difference axis.

Both the blue line current amplitude and the yellow line current amplitude behave in the same way, having operating curves corresponding to the curve 12 in which the corresponding starting and full mechanical loading points define a straight line have the same slope and extent as the portion SF of the curve 12.

The current amplitude at S, the starting current, is, in this example, more than ten times the amplitude of the current at F, the current amplitude at full mechanical loading.

We have now found that if the supply voltage is varied, there is a change in the slope of the characteristic between starting and full load phase current, and that the phase difference at the full load phase current varies non-linearly with the supply voltage, the phase difference increasing slightly as the supply voltage increases and vice versa. In Fig. 2, the characteristic for 120% nominal supply voltage, for the motor with the characteristic 12 at 100% nominal supply voltage, is represented by a curve 12*a* and the corresponding characteristic for 80% nominal supply voltage is represented by a curve 12*b*. On the curves 12*a* and 12*b* the points corresponding to points S, F and N are indicated at S*a* and S*b*, F*a* and F*b* and N*a* and N*b* respectively.

Any condition which results in the phase current amplitude and the phase difference defining a point between the amplitude axis and the linear portion is a fault condition and can, in accordance with the present invention, be detected by comparing the line current amplitude and phase difference values at the point in question with those defined by a predetermined relationship of the form $y = a-(x - b)$ where y = amplitude, x = phase difference, and a and b are independent of amplitude and phase difference.

Fig. 3 shows apparatus for comparing line current amplitude and phase difference values, for one phase, with such a relationship. A voltage signal of amplitude V, provided by means not shown, is in phase with but not necessarily proportional to the red line to yellow line voltage of the red phase of a supply to an induction motor (not shown). Another voltage signal of amplitude I, provided by means not shown, is in phase with and proportion to the corresponding red line current. The signals of amplitude V and I are supplied to a phase discriminator 14 which in response thereto produces a voltage signal Φ_v which is proportional to the phase difference between the signals of amplitude V and I. In other words $\Phi_v = K\Phi$ where Φ is the phase difference and K is a factor of proportionality having units of volts per degree.

The signal of amplitude I is also supplied to an inverter 15 which produces the signal —I which is proportional to I and of opposite polarity to the signal Φ_v. The signal —I is supplied to a voltage dividing potentiometer P1 which divides the signal —I by a factor m to produce a voltage signal $-(1/m).I$.

A comparator 16 is supplied with a reference voltage Φ_{cv} set by a potentiometer P_2 which receives a voltage at a terminal 17. The comparator 16 tests the signals Φ_v and $-(1/m).I$ with the equation

$$I = m(\Phi_v - \Phi_{cv})$$

by comparing the difference $[\Phi_v - (1/m) . I]$ with the reference voltage Φ_{cv}.

If $[\Phi_v - (1/m) . I] > \Phi_{cv}$, the comparator 16 produces zero output voltage.

If $[\Phi_v - (1/m) . I] < \Phi_{cv}$, the comparator 16 produces an output voltage sufficient to energise a relay unit 18. This output voltage is referred to hereinafter as the fault indicating output voltage. Since $\Phi_v = K\Phi$, $I = m(\Phi_v - \Phi_{cv})$ may be written

$$I = mK(\Phi - \Phi_c)$$

where Φ_c is offset phase difference. Furthermore, since we may relate I to the line current amplitude I_L by the equation $I = RI_L$ where R is a constant having the dimensions of resistance, the equation for the line 13 can be written

$$I_L = (1/R)\, mK\, (\Phi - \Phi_c)$$

In one example of means for sensing line current and producing a signal representative of the line current amplitude,

$$R = R_B/n$$

where R_B is a burden resistor impedance and n a current transformer ratio, so that the equation for the line current amplitude may be written

$$I_L = n/R_B \,.\, mK(\Phi - \Phi_c)$$

The energisation of the relay unit 18 is used to open a circuit breaker having contacts in the supply lines to the motor (not shown). Since it is necessary to break the connections in all three phases of a three phase supply to a three phase induction motor whenever a fault occurs, the relay unit 18 controls a circuit breaker with three contact sets such as the contact sets 54 of Fig. 1 and is arranged to be energised by the fault indicating output voltage of any one of the three comparators, one of which is the comparator 16 of Fig. 3 and the other two of which are respective comparators of two sets of apparatus as described with reference to Fig. 3 up to and

including the comparator 16 and arranged respectively to receive voltage signals in phase with and proportional to the yellow and blue line currents, and in phase with the yellow line to blue line and blue line to red line voltage V_{Y-B} and V_{B-R}. The potentiometer P_2 can be common to all three comparators.

The inverter 15 may simply be a diode connected to block those half cycles of the signal of amplitude I which have the same polarity as the voltage Φ_v.

The comparator 16 may comprise a two input differential operational amplifier having two summing resistors connecting its inverting input to the discriminator 14 and the potentiometer P_1 respectively, and a level detector at its output to provide an all or nothing output voltage response.

Fig. 4 shows part of the circuitry of the comparator 16 connected to a logic unit 90 of the phase discriminator 14 and to a supply circuit 95 supplying unregulated 10 volts direct current to the logic unit 90 of the phase discriminator 14 and to two points 101 and 102 in the circuitry of the comparator 16. The logic unit 90 in this example is a CMOS 4011 integrated circuit having its positive supply input terminal V_{DD} connected to the positive rail X of the unregulated 10 volts d.c. supply circuit 95 and its negative supply input terminal V_{SS} connected to the ground rail 96 of the supply circuit 95.

The supply circuit 95 has an input transformer 97 which has its primary winding WP connected across two of the three phase supply lines at points closer to the source (not shown) of the three phase supply than the breaker contacts 54. A full wave rectifying diode bridge BS is connected across the secondary winding WS of the transformer 97 and the resultant unregulated 10 volt d.c. supply at the output terminals constituted by the rails X and 96, is smoothed by a parallel combination of a capacitor 98, and a resistor 99 connected between the rails X and 96.

The logic unit 90 has three input terminals S_V, S_I and 103 and an output terminal S_D. At the output terminal S_D pulses are produced the height of which varies linearly with the d.c. supply voltage applied between the terminals V_{DD} and V_{SS} by the supply circuit 95.

The comparator 16 includes a two input differential operational amplifier 61 having its non-inverting input terminal R connected to the junction of two series connected resistors R20 and R21 which are connected in series with the potentiometer P2 between the unregulated supply rails X and 96. The inverting input terminal S_B of the amplifier 61 is arranged to be the summing junction of three equal resistors R17, R18 and R19 which, respectively, connect the input terminal S_B to the output terminal S_D of the logic unit 90, the movable contact of the potentiometer P1 and the unregulated positive supply rail X. A capacitor C1 couples the inverting input terminal S_B to the output terminal 104 of the amplifier 61. It is arranged that the output level at the output terminal 104 is high when the voltage at the non-inverting input terminal R is higher than the average voltage at the inverting input terminal S_B over a period of 10 milliseconds, and that conversely the output level at the output terminal 104 is low when the voltage at the non-inverting terminal R is lower than the average voltage at the inverting input terminal S_B over 10 milliseconds.

The output pulses at the terminal S_D form a square wave with a lower level of zero volts and an upper level equal to the unregulated positive voltage on the positive rail X, which is normally 10 volts and each leading edge is initiated by a triggering pulse supplied to the input serminal S_v and each trailing edge is initiated by a triggering pulse supplied to the input terminal S_I of the logic unit 90 which thus acts as a bistable circuit. It is arranged that the voltage at the inverting terminal S_B is lower than the voltage at the non-inverting terminal R when triggering pulses are not supplied to the terminal S_V and there is no voltage across the potentiometer P1 so that the resistor RB is in effect connected directly to the zero rail 96. This ensures that a high level output signal appears at the output terminal 104 of the amplifier 61 if no triggering pulses are supplied to the input terminal S_V of the logic unit 90.

The triggering pulses supplied to the terminal S_V occur at the times of 0° and 180° in the cycles of red line to yellow line voltage, and the triggering pulses supplied to the terminal S_I occur at the times of 0° and 180° in the cycles of the corresponding red line current and can be supplied by circuits which are described hereinafter. Since the line current lags the line to line voltage by a phase difference which is between about 50° and 130°, when the motor is operating normally and there is no fault current, the time interval between a triggering pulse at the terminal S_v and the next to arrive at the terminal S_I is a direct measure of this phase difference, and the square wave at the output terminal S_D has a period of 10 milliseconds and a mark-space ratio which varies with the phase difference measured. The average voltage value of the square wave at S_D over 10 milliseconds is therefore also a direct measure of the phase difference between the line current and the corresponding line to line voltage. It can be shown that the value of the factor K of the comparator 16 including the circuitry thereof in Fig. 4 varies proportionally with the positive voltage on the positive rail X so that a graph of I against Φ for the embodiment of Figs. 3 and 4 is a set of straight lines with different slopes and equal intercepts on the Φ axis. Three of these straight lines are illustrated in Fig. 5, a line 13 which corresponds

to the voltage on the rail X being 100% of 10 volts, a line 13*a* which corresponds to the voltage on the rail X being 120% of 10 volts and a line 13*b* which corresponds to the voltage on the rail X being 80% of 10 volts. For any particular value of the voltage on the rail X, the output level at the output terminal 104 of the amplifier 61 switches from low to high whenever the point defined by the prevailing values of I and Φ move from the area to the right of the straight line defined by $I = mK(\Phi - \Phi_c)$ to the area to the left of this line as viewed in Fig. 5. Hence it will be seen that the circuitry of Fig. 4 enables the characteristic of the comparator 16 to adjust its slope automatically with variation in the supply voltage to an attitude substantially parallel to the starting portion of the motor characteristic. For example, if the supply voltage is initially low, the motor characteristic is the curve 12*b* and the comparator characteristic is the line 13*b*. If the supply voltage returns to normal, the motor characteristic becomes the curve 12, and the comparator characteristic swings to become the line 13. Similarly, the comparator characteristic is line 13*a* when the motor characteristic is the line 12*a*.

Fig. 6 shows in more detail the circuitry of Fig. 4 and the circuit for supplying triggering pulses to the input terminal S_I. It will be seen that the circuitry includes in addition a non-linear resistor R_o connected in parallel with the resistor R20. The purpose of this non-linear resistor R_o is to provide a non-linear variation of the intercept Φ_c of the comparator characteristic with phase difference axis which substantially follows the variation in the position of the full load current point F of the motor characteristic with variation in the supply voltage. Fig. 7 is a graph of I against Φ corresponding to Fig. 5 but showing the characteristics 13′, 13′*a* and 13′*b* obtained with the non-linear resistor R_o present.

The bistable logic unit 90 consists of the four NAND gates of the CMOS 4011 connected as shown in Fig. 6 so that logic '0' on the output terminal of the NAND gate 3 blocks both NAND gates 1 and 4 and imposes a logic '0' at the output terminal of the NAND 2 which serves as the output terminal S_D of the unit 90. One input terminal 103 of the NAND gate 3 is held at logic '1' during operation, the terminal 103 being connected to the junction of the two series connected resistors R15 and R16 connected between a + 12 volts stabilized positive supply rail 105 and the ground rail 96. The resistor R16 is large compared with the resistor R15, for example R15 may be 33 kilohms and R16 be 1 megohm. A capacitor C2 connected in parallel with the resistor R16 temporarily blocks the gate 3 when the supply voltage is initially applied between the rail 105 and 96 by temporarily holding the input terminal 103 at logic '0', and thus prevents spurious switching of the output at the terminal 104 to the high level. A resistor R_s coupled one input terminal of the gate 2 to the ground rail 96 so that this gate is temporarily blocked with a logic '0' at its output terminal S_D when the supply voltage is initially applied. In operation, positive triggering pulses as illustrated at 106, are supplied to the terminal S_I so that at the output terminal of the gate 3 a train of closely spaced positive square pulses, as illustrated at 107, appears, the trailing edge of edge square pulse corresponding to the leading edge of a respective positive triggering pulse. Thus one input terminal of each of the gates 1 and 4 receives a logic '1' except during a triggering pulse at the terminal S_I. Consequently, if a triggering pulse arrives at the terminal S_V between the arrivals of two successive triggering pulses at the terminal S_I, the output at the output terminal S_D is set at logic '1' by the arrival of the triggering pulse at the terminal S_V. This logic level '1' remains at the terminal S_D until the arrival of the next triggering pulse at the terminal S_I whereupon the level at the terminal S_D is reset to logic '0' at which the output level remains until another triggering pulse arrives at the terminal S_V between two triggering pulses at the terminal S_I. Thus there are produced square pulses at the output terminal S_D, each having a leading edge initiated by the leading edge of triggering pulse at the terminal S_V and a trailing edge initiated by the leading edge of a triggering pulse at the terminal S_I. The triggering pulses supplied to the terminal S_I are arranged to be larger than those supplied to the terminal S_V in that the pulses at S_I decay more slowly than those at S_V, and so that if the triggering pulses at the two terminals S_I and S_V arrive simultaneously, as is the case if the line to line voltage is in phase with the line current, the gate 3 prevails and holds the output level at the output terminal S_D at logic '0', thereby causing the output level at the terminal 104 to be high. Failure of triggering pulses to arrive at the terminal S_V also results in a continuous logic '0' at the terminal S_D and a high output level at the terminal 104.

The triggering pulses supplied to the input terminal S_I are produced in the following manner.

One end of the second SG of the current transformer G of Fig. 1 is connected to the zero volts supply line and through a burden resistor RB to its other end. A current S_I which is in phase with and proportional to the red line current flows through the burden resistor RB when the motor M is connected to the three phase supply. The said other end of the secondary, which will now be referred to as the active end, is coupled through two series resistors R4 and R5 to the non-inverting input terminal of an operational amplifier A_1 whose inverting input terminal is con-

nected through a resistor R6 to the zero supply line and through a resistor R8 to the + 12 volts supply line. A zener diode Z1 is connected as shown to clip the negative voltages supplies to the non-inverting input terminal of the amplifier A_1.

The active end of the secondary SG is also coupled through two series resistors R10 and R11 to the inverting input terminal of an operational amplifier A_2 whose non-inverting input terminal is connected through a resistor R12 to the zero volts supply line and through a resistor R13 and to a − 12 volts supply line. A zener diode Z2 clips positive voltages supplied to the inverting input terminal of the amplifier A_2. The resistors R8 and R13 are very large, e.g. 10 megohms, and the resistors R6 and R12 are relatively small, e.g. 22 kilohms, so that the output of the amplifier A_1 is a train of positive-going voltage pulses corresponding to the positive half cycles of the red line current, and the output of the amplifier A_2 is a train of positive-going voltage pulses corresponding to the negative half cycles of the red line current. The leading edges of these positive-going pulses occur substantially at the 0° and 180° phases of the red line current. The positive-going pulses are differentiated and the negative-going spikes resulting from their trailing edge are suppressed by an arrangement of capacitors C3 and C4, diodes and a resistor R14 coupling the output terminals of the amplifiers to one input terminal S_I of a phase discriminator circuit, so that only the positive-going spikes, with leading edges 10 milliseconds part, appear in the input terminal S_I.

The time constants of the capacitors C3 and C4 with the resistor R14 are such that the pulses at the input terminal S_I are effective to hold the output of the gate 3 at the logic '0' level throughout the a time which is long enough to ensure that the output level at the terminal S_D remains at logic '0' even when the line current leads the corresponding line to line voltage by up to 5°. Fig. 8 illustrates graphically the variation of the average voltage V_{AV} at the terminal S_D with phase difference Φ and shows the zero volts obtained when the line to line voltage leads the line current by up to 5°.

Fig. 10 shows the circuit for producing triggering pulses to be supplied to the terminal S_V.

Between each pair of the lines 51 to 53 a series combination of a resistor and a diode bridge including a IRE-diode (infra-red emitting diode) is connected. Whenever there is voltage between the red line and the yellow line an IRE-diode DE conducts. Similarly the other IRE-diodes conduct whenever there is voltage between the yellow and blue lines and between the blue and red lines respectively. Each of the IRE-diodes is arranged to irradiate a respective photo-transistor only one of which is shown, namely the photo-transistor T2 which is irradiated by the red-yellow IRE-diode DE. Each IRE-diode and photo-transistor constitutes an electro-optical isolator.

The collector of the photo-transistor T2 is connected through a resistor R7 to the positive supply line 105 at + 12 volts. The emitter of the photo-transistor T2 is connected directly to a zero volts supply line 96. A very large resistor R9 couples the base of the photo-transistor T2 to the zero volts supply line. Consequently, throughout almost the whole of each half-cycle of red line to yellow line voltage V_{R-Y} the collector of the photo-transistor T2 is at + 12 volts, the collector voltage switching to zero volts at the end of each half cycle for a short time. Part of the resultant square wave at the collector of the transistor T2 is shown at 108.

This square wave is amplified and inverted by an inverting buffer 111, which may be a CMOS 4049 integrated circuit, and the inverted waveform is differentiated by a differentiating circuit consisting of a capacitor C6 and a resistor R29. The resultant negative pulses are suppressed by a diode D15 connected in parallel with the resistor R29 and the resultant positive pulses 108 are supplied to the terminal S_V. The leading edges of the positive pulses at the terminal S_V occur substantially at 0° and 180° phases of the red to yellow line voltage V_{R-Y}. If the IRE-diode DE or the phototransistor T2 fails to operate, the voltage at the terminal S_V drops to zero and remains there so that no pulses are supplied to the logic unit 90 at this terminal S_V.

In operation, the output of the amplifier 61 stays at substantially zero volts when the average algebraic sum over one cycle of the voltages at the summing function S_B is greater than the voltage at the non-inverting input of the amplifier 61, whereas the output of the amplifier 61 rises to + 12 volts with a time constant determined by the values of C1, R17, R18 and R19 when the said sum is less than the voltage at the non-inverting input. The time then taken by the comparator 60 to change from an output signal of substantially zero volts to an output signal of + 15 volts depends on the time constant and the magnitude of the difference between the sum one ends of resistors R17, R18 and R19, and the voltage at the non-inverting input.

The output of the amplifier 61 is connected to the anode of an isolating diode D7 the cathode of which is connected to one end of a resistor R22 which is in series with the resistor R23 as shown in Fig. 8. A junction point 100 at the ends of the resistors R22, R23 and R24 is connected to the base of a first NPN transistor T3 of a Darlington pair T3 and T4.

The capacitor C3 connected in parallel with the series combination of the resistors R23 and R24 protects the Darlington pair against

high current surges which may occur in response to high amplitude lines current sensed by the current transformer G or either of the two other current transformers not shown.

The emitter of the second NPN transistor T4 of the Darlington pair is connected to the cathode of a Zener diode Z3 the anode of which is connected to the zero volts supply line. The collectors of the two NPN transistors T3 and T4 are connected through the operating coil 71 of the magnetically latched relay 55 and a manually operable single pole two-way set-reset switch 80 to the + 12 volts supply line. In Fig. 8 the movable contact 81 of the switch 80 is shown in its set position. When the contact 81 is in its reset position, the coil 71 and the Darlington pair are disconnected from the + 12 volts supply line, and the reset coil 72 of the relay 55 is connected directly between the + 15 volts and zero volts supply lines.

A resistor R26 is connected in parallel with the series combination of the coil 71 and the Darlington pair, so that the zener diode Z3 conducts and the resistor R26 provides an emitter bias voltage for the transistor T4. The arrangement is such that as soon as the voltage at the point 100 exceeds + 4 volts, the Darlington pair conducts sufficient current to cause the relay coil 71 to switch the contact 56 to a circuit breaker operating position in which the contact sets 54 are opened. Since the relay is magnetically latched, the contact 56 is held then in the circuit breaker operating position until the coil 72 is energised by manual operation of the switch 80.

The contact 56 will be held in the circuit breaker operating position once it has been switched into that position by energisation of the coil 71, even if the + 12 volt supply subsequently fails.

The diode D14 protects the Darlington pair against the back e.m.f. of the coil 71 when the contact 81 is switched to the coil 72.

A series combination of a diode D4 and the potentiometer P1 is connected in parallel with the burden resistor R_B. The potentiometer P1 is also of two other such series combinations, completed by diodes D5 and D6 respectively, which are connected in parallel with respective burden resistors (not shown) of the yellow and blue line current transformers (not shown).

It would be possible to have separate diodes D4, resistors R6 and potentiometers P1 for each of the three phases. However, apart from using extra components, such an arrangement has a further disadvantage in that it tends to produce spurious indication of a short circuit fault in the motor starting period during which a considerable transient current asymmetry appears in the three supply lines. By using a common potentiometer P1 for all three phases as shown in Fig. 6 the effects of current asymmetry are averaged out over the 20 millisecond period of the supply frequency.

A high current override coupling shown in Fig. 8 and comprising a diode D11 in series with a resistor R19 and a capacitor C2 in parallel with two resistors R20 and R17 couples the active end of the secondary of the transformer G to the zero volts supply line.

Two further high current override couplings are provided by coupling the respective active ends of the respective secondaries of the two current transformers not shown through diodes D12 and D13 to the junction of the diode D11 with the resistor R19.

In operation positive cycles of the secondary current of the transformer G flow through the burden resistor RB and the high current override coupling D11, R19 and R20, and negative cycles thereof flow through the burden resistor RB and the series combination D4 and P1.

If a red, yellow or blue line current greater than the motor starting current suddenly appears the Darlington pair is triggered by the respective high current override coupling, which includes the capacitor C3, before the NAND gates and the comparator of the respective phase have time to act. Thus the high current override couplings ensures that the supply 50 is protected quickly when a current whose amplitude exceeds the starting amplitude at S on the curve 12 appears. The values of the components involved in the high current override couplings are such that the Darlington pair cannot be operated by the high current override couplings when the line currents are at S or below.

The reference voltage source Ro, R20, R21 and P2 is common to the comparators for all three phases, and the respective operational amplifiers have the diode D7, and diodes D8 and D9 at their outputs coupling them to the resistor R22 which is common to all three phases. The switch 80, relay 55, the Darlington pair, resistor R18 and Zener diode Z3 are common to the three phases also.

Connections to the non-inverting inputs of the yellow and blue phase operational amplifiers (not shown) are shown at Y and B respectively. Resistors R27 and R28 couple the sliding contact of the potentiometer P1 to the respective inverting inputs of the yellow and blue phase operational amplifiers. The potentiometer P1 being common to the three phases does not interfere with the proper operation of the respective comparators since the current supplied to the potentiometer P1 consists of three negative half waves with 120° phase differences between the corresponding full waves.

The constants m and Φ_{cv} in the equation

$$I = m(\Phi_v - \Phi_{cv})$$

for each of the three phases are set by adjust-

ment of the sliding contact of the potentiometer P1 and adjustment of the variable resistor P2, the potentiometer P1 determining the constant m, and the resistor P2 determining the constant Φ_{cv}. The supply level of +10 volts included in this voltage is removed by the biasing of the operational amplifiers at their non-inverting inputs. Line currents establish a range of possible voltage amplitudes across the burden resistors in accordance with the ratios of the current transformers and the impedances of the burden resistors. The setting of the sliding contact of the potentiometer P1 establishes at the summing junction S_B a range of possible voltage values which are proportional to the possible line current amplitude and are scaled so as to be representative of ($^1/m$) in relation to the values of phase difference Φ represented by the outputs of the three groups of four NAND gates such as the gates 1 to 4 of Fig. 5. Considering the relation for line current

$$I_L = {}^n/_{R_B}.mK\,(\Phi - \Phi_c)$$

then, if, for a particular motor we measure the slope, in amperes per degree, of the characteristic SE (Fig. 4) and the required value of Φ_c in degrees, then the required value of m may be calculated from the equation

$$\text{slope of characteristic} = {}^n/_{R_B}.mK,$$

convenient values of n, R_B and K having been chosen. The potentiometer P1 may then be set to give the required value of $^1/m$. Similarly, the setting of variable resistor P2 may be calculated from the required value of Φ_c.

The movement, when a two phase short circuit fault occurs, of the point representing line current and difference in phase between line current line to line voltage towards the line to line voltage towards the line current axis in Fig. 2 is due to the fault current being almost in phase with the line to line voltage, i.e. the instantaneous voltage between the two supply lines between which the fault current flows, the path of the fault current providing little reactance. In the case of a three phase symmetrical short circuit fault, the respective fault currents flowing from each supply line are almost in phase with the respective line to neutral voltages which lag the corresponding line to line voltages by 30°. Furthermore, most if not all three phase faults start as two phase short circuit faults in which a short circuit appears between two supply lines. The embodiment described will nevertheless detect three phase symmetrical short circuit faults since the presence of such faults also reduces the difference in phase between the line current and the line to line voltage and causes the operating point in Fig. 7 to move to the left of the line 13'.

A constructed embodiment of the present invention is used in conjunction with a 1100 volt, 45 horsepower flameproof induction motor in accordance with specification no 291/1962 of the Nation Coal Board of the United Kingdom, available from Horace Green & Co, Limited, Keighley, Yorkshire, England, this motor giving a set of characteristic curves in accordance with Fig. 2. A suitable non-linear resistor Ro is a voltage dependent resistor such as the Mullard type E299DD/P230 VDR, the resistor R20 being 22 kilohms, the resistor R21 being 12 kilohms and the potentiometer P2 giving a maximum resistance of 4.7 kilohms. For the resistor R_S, a suitable value is found to be 56 kilohms. Each of the capacitors C3 and C4 is 3600 picofarads and the resistor R14 is 68 kilohms, the capacitor C6 (Fig. 10) being 3600 picofarads and the resistor R29 being 50 kilohms. The potentiometer P1 gives a maximum resistance of 470 ohms, and each of the resistors R17, R18 and R19 is 150 kilohms.

Suitable integrated circuits to serve as the amplifiers A1 and A2 are 531 circuits. The amplifier 61 is, in the constructed embodiment, 741 circuit.

An alternative to the non-linear resistor Ro is a series combination of a 5.1 volt zener diode and a 150 kilohm resistor, the zener diode being so arranged that its cathode is connected to the unregulated supply rail X.

The time constant of the unregulated supply 95 should be as small as possible so that the voltage between the rails X and 96 changes rapidly in response to change in the three phase supply.

CLAIMS

1. Apparatus for sensing short circuit faults in alternating current supply lines, the apparatus including means for sensing line current in an alternating current supply line and producing signals representative of the sensed amplitude and a phase of line current flowing in operation, means for sensing the line to line or line to neutral voltage of the supply line and producing a signal representative of a phase of the line to line or line to neutral voltage, difference means coupled to receive the signals which are representative of the phases of the said current and voltage and arranged to produce in response thereto a signal having a measure which varies substantially directly with difference between the said phases, and means for comparing a relationship of the signal representative of sensed current amplitude and the said signal produced by the difference means with a predetermined relationship of amplitude and phase difference and producing in response thereto an output signal representative of whether or not the sensed current amplitude is larger than the corresponding amplitude as determined by the said predetermined relationship for the said difference between the said

phases, the said predetermined relationship being such as to vary with the said line to line or line to neutral voltage.

2. Apparatus according to claim 1, wherein there is provided means for interrupting at least the said supply line in response to the said output signal being representative of the sensed current amplitude being larger than the said corresponding amplitude, the interrupting means being coupled to the comparing means to receive the said output signal.

3. Apparatus for sensing short circuit faults in a three phase supply, the apparatus including means for sensing each line current in three phase lines and producing signals representative of the sensed amplitudes and phases of the line currents flowing in operation, means for sensing the line to line or line to neutral voltages of the supply lines and producing signals representative of phases of the line to line or line to neutral voltages, difference means coupled to receive the signals which are representative of the said phases and arranged to produce in response thereto three signals each of which has a measure which varies substantially directly with difference in phase between the respective line current and line to line or line to neutral voltage of a respective one of the three phase lines, means for comparing for each phase line a relationship of the respective one of the signals representative of sensed current amplitude and the respective one of the signals produced by the difference means with a predetermined relationship of amplitude and phase difference and producing in response thereto an output signal representative of whether or not any one or more of the sensed current amplitudes is larger than the corresponding amplitude as determined by the respective predetermined relationship for the respective one of the said differences in phase between the respective line current and line to line or line to neutral voltage, and means for interrupting the three supply lines in response to the said output signal being representative of any one or more of the sensed current amplitudes being larger than the said corresponding amplitude, the interrupting means being coupled to the comparing means to receive the said output signal, and the respective predetermined relationships being such as to vary with the respective line to line or line to neutral voltages.

4. Apparatus for sensing short circuit faults in alternating current supply lines, the apparatus including means for sensing line current in an alternating current supply line and producing a signal representative of the sensed amplitude and current phase triggering pulses each corresponding to a selected phase of line current flowing in operation, means for sensing the line to line or line to neutral voltage of the supply line and producing voltage phase triggering pulses each corresponding to a selected phase of the line to line or line to neutral voltage, bistable means coupled to receive the said current and voltage phase triggering pulses and arranged to produce in response thereto a train of phase difference pulses each having a leading edge initiated by a respective voltage phase triggering pulse and a trailing edge initiated by a respective current phase triggering pulse whereby the width of the pulse varies substantially directly with difference between the said phases, means for comparing a relationship of the signal representative of sensed current amplitude and an average value established by the train of pulses produced by the bistable means with a predetermined relationship of amplitude and phase difference substantially of the form $y = a(x - b)$ where y = amplitude, x = phase difference and a and b are independent of x and y and producing in response thereto an output signal representative of whether or not the sensed current amplitude is larger than the corresponding amplitude as determined by the said predetermined relationship for the said difference between the said phases.

5. Apparatus for sensing short circuit faults in a three phase supply, the apparatus including means for sensing each line current in three phase lines and producing signals representative of the sensed amplitudes and respective current phase triggering pulses each corresponding to selected phases of the line currents flowing in operation, means for sensing the line to line or line to neutral voltages of the supply lines and producing respective voltage phase triggering pulses respectively corresponding to selected phases of the line to line or line to neutral voltages, three bistable means coupled to receive respectively the triggering pulses which correspond to the respective lines and arranged to produce in response thereto three trains of phase difference pulses in each of which each pulse has a leading edge initiated by a respective voltage phase triggering pulse and a trailing edge initiated by a respective current phase triggering pulse whereby the width of the pulse varies substantially directly with difference in phase between the respective line current and line to line or line to neutral voltage of a respective one of the three phase lines, means for comparing for each phase line a relationship of the respective one of the signals representative of sensed current amplitude and an average value of the respective one of the trains of phase difference pulses with a predetermined relationship of amplitude and phase difference substantially of the form $y = a(x - b)$ where y = amplitude, x = phase difference and a and b are independent of x and y and producing in response thereto an output signal representative of whether or not any one of more of the sensed

current amplitudes is larger than the corresponding amplitude as determined by the respective predetermined relationship for the respective one of the said differences in phase between the respective line current and line to line or line to neutral voltage, and means for interrupting the three supply lines in response to the said output signal being representative of any one or more of the sensed current amplitudes being larger than the said corresponding amplitude, the interrupting means being coupled to the comparing means to receive the said output signals.

6. Apparatus according to claim 4 or 5, wherein the selected phases ate 0° and 180° in each cycle of the voltage or current concerned.

7. Apparatus according to claim 5, wherein the supply lines are connected to a direct-on-line starting three phase squirrel cage induction motor and the predetermined relationship is, for each phase line, of the form

$$I_L = \frac{n}{R_B} . mk\,(\Phi - \Phi_C)$$

where I_L is the amplitude of the respective line current in amperes,

m is a dimensionless contstant,

K is a factor which varies with line to line voltage for the phase and has units of voltage per degree,

R_B is a burden resistance in ohms.

n is the dimensionless ratio of a current transformer i.e. the ratio of secondary to primary turns,

Φ is the phase difference between the respective line to line voltage and line current measured in degrees, and

Φ_c is a phase difference which varies with line to line voltage for the phase and is measured in degrees.

8. Apparatus according to claim 2, 3, 5 or 7, wherein the said interrupting means is arranged to act on the supply line or lines at a position between the source of the supply and the said sensing means.

9. Apparatus according to any preceding claim, wherein the or each means for sensing line current and producing signals representative of the amplitude and a phase of line current flowing in operation include a current transformer core and secondary winding which, in use, are so arranged that the supply line for conducting the line current to be sensed forms the primary of the current transformer thus constituted.

10. Apparatus according to any preceding claim, wherein the or each means for sensing voltage includes an electro-optical isolator adapted to be actuated, in use, by line to line to neutral voltage.

11. Apparatus according to claim 10, wherein the or each means for sensing voltage is such as to sense a line to line voltage of the respective supply line and the electro-optical isolator includes an Infra Red Emitting diode connected in series with a resistor to form a series combination which in use is connected between the respective supply line and another supply line.

12. Apparatus according to claim 1, wherein the said signals are voltage signals and the said comparing means includes an inverter arranged to receive a signal representative of the amplitude and a phase of sensed line current and to produce in response thereto an inverter output signal representative of the amplitude of the sensed line current and of opposite polarity to the said signal proportional to difference, a scaler connected to the inverter to receive the inverter output signal and to divide the magnitude of the inverter output signal by a predetermined factor, and a comparator connected to the scaler and to receive the said signal produced by the difference means and to a source of reference voltage of a predetermined magnitude and polarity in accordance with the said predetermined relationship.

13. Apparatus according to claim 1 or 2 or 4, wherein the comparing means includes a differential amplifier having one differential input thereof coupled to the summing point of a plurality of summing resistors and having the other differential input thereof connected to means for supplying thereto a reference signal which varies the said predetermined relationship with the said line to line or line to neutral voltage.

14. Apparatus according to claim 8, wherein override means are provided so coupling the means for sensing the or each line current to the means for interrupting the or each phase line that if the sensed current amplitude or or or more of the sensed current amplitude exceeds a predetermined value, the override means actuates the interrupting means before the said output signal is representative of the sensed current amplitude or one or more of the sensed current amplitudes being larger than the said corresponding amplitude or amplitudes.

15. Apparatus according to claim 1 and substantially as described hereinbefore with reference to Fig. 3 of the accompanying drawings.

16. Apparatus according to claim 5 and 7 substantially as described hereinbefore with reference to Figs. 1, 4, 6, 8 and 10 of the accompanying drawings.

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